An over review of desertification in Xinjiang, Northwest China

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Abstract: Desertification research in arid and semi-arid regions has always been actively pursued. In China, the problem of desertification in Xinjiang has also received extensive attention. Due to its unique geography, many scholars have conducted corresponding research on the desertification status of Xinjiang. In this paper, we comprehensively reviewed desertification in Xinjiang, and compared the underlying mechanisms of desertification and the status of desertification conditions after the implementation of ecological control projects. On a larger scale, desertification in Xinjiang can be divided into soil salinization inside oases and sandy desertification on the edges of oases. Human activities are considered the main cause of desertification, but natural factors also contribute to varying degrees. Research on the mechanisms of desertification has effectively curbed the development of desertification, but unreasonable use of land resources accelerates the risk of desertification. For desertification control, there are several key points. First, desertification monitoring and the early warning of desertification expansion should be strengthened. Second, monitoring and reversing soil salinization also play an important role in the interruption of desertification process. It is very effective to control soil salinization through biological and chemical methods. Third, the management of water resources is also essential, because unreasonable utilization of water resources is one of the main reasons for the expansion of desertification in Xinjiang. Due to the unreasonable utilization of water resources, the lower reaches of the Tarim River are cut off, which leads to a series of vicious cycles, such as the deterioration of ecological environment on both sides of the river and the worsening of desertification. However, in recent years, various desertification control projects implemented in Xinjiang according to the conditions of different regions have achieved remarkable results. For future studies, research on the stability of desert-oasis transition zone is also significantly essential, because such investigations can help to assess the risk of degradation and control desertification on a relatively large scale.

Keywords: desertification; soil salinization; sandy desertification; desertification control; soil wind erosion; human activities; Tarim Basin

1 Introduction

Desertification is described as land degradation in arid, semi-arid, and dry subhumid areas due to the negative impacts of human activities and climatic variations. The original definition is the destruction or diminution of the biological potential of the land (Schlesinger et al., 1990). The total

area of global drylands accounts for around 41.00% of the Earth's land surface and is home to more than 38.00% of the global population ($6.5×10^9$ in 2013) (D'Odorico et al., 2013). Desertification can have numerous negative consequences, including increased soil salinity and toxicity, loss of soil resources, and changes in vegetation composition (Schlesinger et al., 1990; Rengasamy, 2006; Simon, 2006). Recent studies have indicated that desertification will occur on the edges of the desert; however, dryland areas that are not close to the edges of the desert may also be at risk of desertification (Wang et al., 2017; Jiang et al., 2019).

Desertification monitoring is one of the most popular methods widely used in studies related to desertification analysis. Desertification monitoring indicators are factors used to measure the degree of desertification expansion and the change trends of desertification, which are the necessary conditions to carry out desertification research effectively, objectively, and quantitatively. Desertification monitoring indicators must be quantitative parameters that are prone to change (D'Odorico et al., 2013; Dharumarajan et al., 2018; Jiang et al., 2019). They can accurately and sensitively reflect the slight changes of desertification and are easily measured either directly or indirectly. Desertification monitoring should combine physical, biological, and sociological factors (Liu and Dong, 2003), and these indicators vary in different studies.

There are many foundational studies for desertification monitoring that use the vegetation index, and these approaches have been used on the national and global scales (Sommer et al., 2011; Imeson, 2012; Bestelmeyer et al., 2013). Since remote sensing technology has been used in natural resource investigations, researchers in various countries began to select multiple indicators, such as the Normalized Difference Vegetation Index (NDVI) (Piao et al., 2005), grass coverage (Bestelmeyer et al., 2013), drought-tolerant plant species (An et al., 2007), land productivity dynamics (Baskan et al., 2017), and many other indicators, to study land desertification and its related contents. Compared to these approaches, traditional field investigations have difficulty in fully meeting the dynamic monitoring of desertification evaluation due to the limitations of timeliness, accuracy, and scale difference. The development of modern aviation and aerospace technology provides a wealth of multispectral (especially the infrared spectrum) and various ground resolution remote sensing image data for remote sensing monitoring of vegetation (Kuenzer et al., 2015). These remote sensing image data have been widely used in vegetation monitoring because of their accuracy, real-time nature, universality, and integrity of coverage area (Andela et al., 2013; Jiang and Shu, 2019; Vagen and Winowiecki, 2019; Wang et al., 2021). Remote sensing image data are effectively used for different indices to evaluate land degradation, salinization, and desertification (Pan, 2001; Zhang et al., 2003; Gong, 2007). In addition to single factors, synthetic indicators of desertification have also been used to assess desertification, such as climate, soil, land use, and socio-economic factors (Dharumarajan et al., 2018). The results of these analyses provide a theoretical basis for sustainable land management in drylands, helping to increase the resilience of local ecosystems all over the world (Banadda, 2010).

Desertification is an important issue in land management in China. From 1950 to 2000, there was a significant increase in desertified land areas in China, with a nearly three-fold expansion from $1.37×10^5$ to $3.85×10^5$ km² (Wang et al., 2012). Furthermore, the desertification rate has risen significantly, from $1.56×10^3$ km²/a during 1950–1975 to $3.60×10^3$ km²/a during 1988–2000 (Wang et al., 2015). The desertified land areas are mainly distributed from the Taklimakan Desert to the Horqin Sandy Land and Hulun Buir Sandy Land in Northwest China. The decrease in vegetation cover in these areas has caused sand transport, leading to various environmental issues (Zhang et al., 2008). There are four sandy lands and eight deserts in China, among which the most severe desertified land areas are distributed in the agro-pastoral ecotones in the northeast and the oases along the inland rivers or in the lower inland rivers in the northwest (Prince, 2002). Xinjiang Uygur Autonomous Region, located in the northwest of China, has made great achievements in combating desertification in recent years. Therefore, this study will review the studies related to the desertification issues and demonstrate the main problems facing desertification in Xinjiang. More importantly, this study can provide a basic reference for desertification control in Xinjiang.

2   Desertification in Xinjiang

Xinjiang is the largest region in China, with an area of 1.60×10^6 km^2. However, due to the natural environment of this region, the land utilization rate is relatively low in Xinjiang compared to other regions in China. Xinjiang is an arid region with little precipitation that is unevenly distributed. The size of unused and hard-to-use land accounts for 61.51% of the total land area in Xinjiang (Wang et al., 2002). Currently, the fragile ecosystem causes the land to be susceptible to desertification. Thus, due to the complex environmental situation in Xinjiang, there is plenty of research on desertification in this region (e.g., Jiang et al., 2019).

There are more than 800 large and small oases in Xinjiang, accounting for 4.27% of the total land area in Xinjiang and carrying more than 95.00% of Xinjiang's population. In comparison, the deserts and Gobi area account for 47.70% of the total land area, and oases are separated and surrounded by these deserts and Gobi area, causing the oases to be unstable (Amuti and Luo, 2014).

The topography, water, and heat conditions of Xinjiang determine that the ecosystem in Xinjiang is simple and low-functioning and the logistics exchange buffer is small, resulting in the balance of the whole system being easily broken and difficult to reverse. The forest coverage of Xinjiang is about 1.68%, while the desert vegetation area accounts for 42.00%, with the vegetation coverage being of 5.00%–15.00% (Gong, 2007). Most of the surface sediments of the two large basins (Tarim Basin and Junggar Basin) are river alluvium, while some are lacustrine deposits (mostly deep loose sand deposits). The arid climate also makes Xinjiang a large area of soil salinization; about 80.00% of the wasteland suitable for agriculture has been salinized. The area of secondary salinization in the existing cultivated land accounts for one-third of the total cultivated land (Fan et al., 2002; Wang et al., 2002).

Human activities are also a non-negligible factor that leads to desertification in Xinjiang. There has been a six-fold increase in the population of Xinjiang between 1953 and 2020 (Zheng et al., 2020). Commensurate with the development of the population, the excessive utilization of water resources has induced the potential factors of land degradation (Jiang et al., 2005). Before the year 2000, uncontrolled water consumption accelerated land desertification. The oases in Xinjiang, which account for only 4.27% of the total land area, consume 55.50% of the surface runoff and 72.00% of the actual water diversion in Xinjiang (Jiang et al., 2005; Gong, 2007). Water resources introduced by oases and canal systems replenished irrigation leakage and groundwater infiltration by 2.56×10^9 m^3/a, resulting in the rise of groundwater level, secondary soil salinization, and swamping (Tian et al., 1999; Wang et al., 2002; Chen et al., 2003).

On the contrary, the amount of water flowing into the lower reaches of rivers, lakes, and desert areas sharply decreases or stops flowing. The lakes shrink or dry up, the groundwater level drops, and the vegetation degrades, leading to land desertification and quicksand invasion (Fan et al., 2002). The Tarim River Basin is a typical example. Since the 1950s, large-scale reclamation in various tributary areas has reduced the amount of water entering the river by 37.50%. The upstream land reclamation consumed 40.00% of the existing water, the middle reaches devoured 43.00%, and only 17.00% flowed into the downstream area. Water resources have also been diverted to agricultural areas, resulting in the shortening of the mainstream of the Tarim River by more than 260 km (Jiang et al., 2005; Peng et al., 2019). Till the year 2000, the groundwater level in the Tarim River Basin dropped from 1–4 to 6–12 m, the vegetation degraded and died, and the tail of the Lop Nur and Taitema Lake dried up and became salt desert.

Researchers have used remote sensing and GIS techniques to analyze and assess the land desertification status in Xinjiang (Li et al., 2004a; Zhang et al., 2015). Li et al. (2004a) applied 274,846 sample areas and remote sensing imagery to classify and monitor the land desertification in Xinjiang during 1999–2000 and the results showed that the total desertified land area in Xinjiang was 1.11×10^6 km^2, occupying 77.08% of the total monitoring area.

The change in desertified land can be obtained by analyzing the land cover data from different years. Figure 1 shows the area changes of desertified land in Xinjiang from 1980 to 2020 using the remote sensing monitoring data of China's land uses released by the Resource Environment and

Data Center of the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences (https://www.resdc.cn). By reclassifying different land use types, the land in Xinjiang can be divided into desertified land and non-desertified land. Specifically, non-desertification land includes cultivated land, forest land, grassland, water area, urban and rural land, industrial and mining land, and residential land. The land use types such as sandy land, Gobi, bare land, and others are divided into desertified land. By calculating the area of non-desertification land and desertification land, we obtained the transition matrix of land desertification in Xinjiang from 1980 to 2020, as shown in Table 2. The transition between desertified land and non-desertified land is a dynamic process, noting that desertification and reversion happened at the same time in Xinjiang (Fig. 2). After 2000, the reversion area was always more significant than the degradation area, and the total non-desertified land area in 2020 was larger than the previous years, indicating that the progress had been made in desertification control. However, some factors cannot be ignored. The degradation mainly took part on the edges of oases, but it may also occur inside oases. The occurrence of desertification is not only caused by natural factors but also by human activities. Thus, ongoing monitoring and studying of the mechanisms behind desertification is essential in Xinjiang, because desertification is a continuous process and an issue of concern.
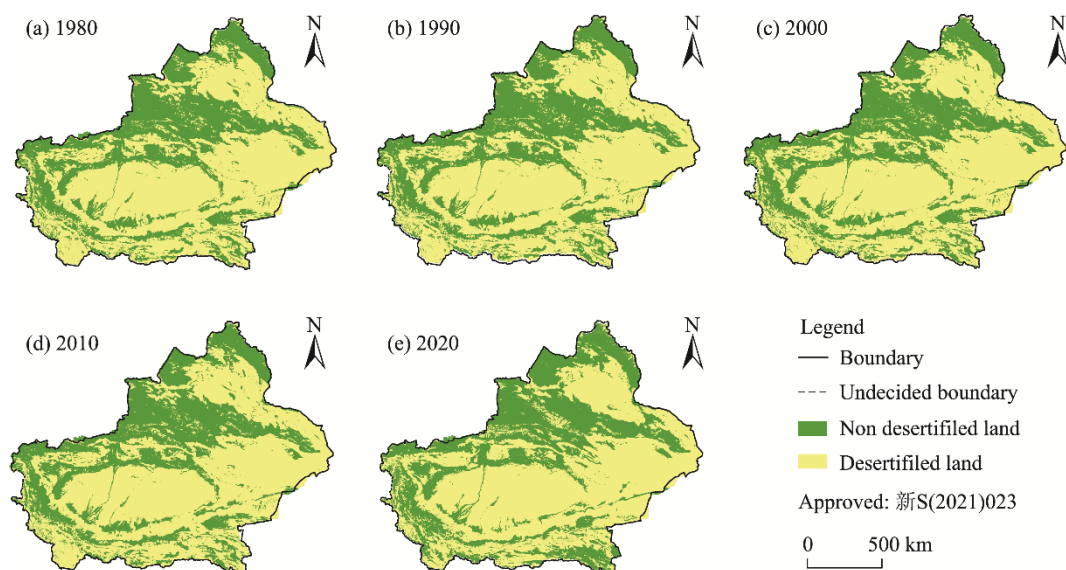

Fig. 1 Spatial distribution of desertified land and non-desertified land in Xinjiang in 1980 (a), 1990 (b), 2000 (c), 2010 (d), and 2020 (e). Note that the figures are based on the standard map (新 S(2021)023) of the Map Service System (https://xinjiang.tianditu.gov.cn/main/bzdt.html) marked by the Xinjiang Uygur Autonomous Region Platform for Common Geospatial Information Services, and the standard map has not been modified.

Table 2 Transition matrix of land desertification in Xinjiang from 1980 to 2020

Period	Area/percentage	NDL→NDL (constant)	DL→DL (constant)	NDL→DL (degradation)	DL→NDL (reversion)
1980–1990	Area (km^2)	628,108	995,226	6301	9519
	Percentage (%)	38.32	60.72	0.38	0.58
1990–2000	Area (km^2)	620,493	988,986	17,116	12,543
	Percentage (%)	37.85	60.34	1.04	0.77
2000–2010	Area (km^2)	631,617	1,006,108	1435	5249
	Percentage (%)	38.41	61.18	0.09	0.32
2010–2020	Area (km^2)	501,230	858,776	135,490	143,353
	Percentage (%)	30.58	52.40	8.27	8.75

Note: NDL, non-desertified land; DL, desertified land.
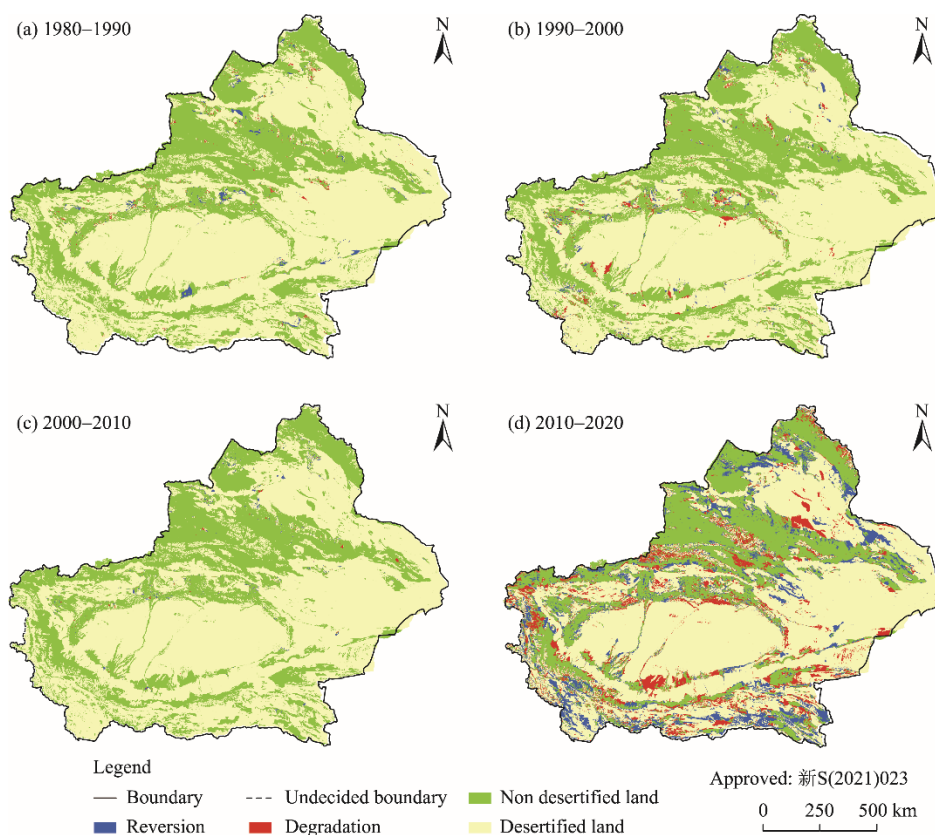
Fig. 2 Spatial distribution of changes in desertified land and non-desertified land as well as land revision and degradation in Xinjiang during the periods of 1980–1990 (a), 1990–2000 (b), 2000–2010 (c), and 2010–2020 (d)

3   Hotspot of desertification studies in the Tarim Basin

The Tarim Basin is considered the hotspot for desertification research among all existing studies. It is the largest inland basin in China and has an area of $5.30×10^5$ km². Affected by regional climatic and environmental factors, the ecosystem around the Tarim River is fragile and its function is limited (Zu et al., 2003). It is essential to understand the ecological changes and environmental protection in similar regions, especially in Xinjiang.

From 1959 to 1983, the percentage of desertified land area in the mainstream of the Tarim River increased from 66.23% to 81.83%, an increase of 15.60% (Wang et al., 2002). From 1991 to 2000, the vegetation coverage in oases was improved, but the degree of desertification in the desert transition zone was strengthened; this is because of the serious human disturbances in the Tarim River Basin (Kasim et al., 2011, 2012). From 1949 to 2002, the population in the Tarim Basin grew from $3.00×10^6$ to $9.00×10^6$, which necessitated the growth of cultivated land. The main reaches of the Tarim River continually shrunk, and the annual water volume was reduced from about $5.00×10^9$ m³ in the 1950s to $4.20×10^9$ m³ in the 1990s (Zhang et al., 2003). Many rivers were intercepted, reservoirs were built, wasteland was reclaimed, and the area of oases was increased; in this way, the oases were developed (Fan et al., 2002). However, due to the interception of rivers and the interference of human activities, the initially fragile ecological environment is overwhelmed, resulting in desertification. The irrational utilization of water resources caused an imbalance in the whole ecosystem. The rapid expansion of cultivated land increased water consumption in the upper reaches, which caused land degradation in the lower reaches. The groundwater depth along the river dropped significantly; large-scale wetlands disappeared and cultivated land was degraded into desert. By 2000, the severely desertified land in the lower reaches of the Tarim River accounted for 52.71% of the total area (Ye et al., 2005). Thus, sufficient water management policies have been

applied to control the desertification progress in the Tarim Basin.

Since 2000, the Chinese government has launched the Ecological Water Diversion Project (EWDP) to restore the eco-environment of the lower reaches of the Tarim River, costing 1.07×10^{10} RMB (Zhou et al., 2009). The analysis of the field monitoring data of nine groundwater monitoring sections and 18 vegetation sampling plots from the dry channels in the lower reaches of the Tarim River during the period of 2000–2002 showed that the groundwater depth has a direct relationship with the composition, distribution, and growth of natural vegetation (Zhou et al., 2009). The declining groundwater level and the significant loss of soil moisture are the dominant factors causing vegetation degradation in the lower reaches of the Tarim River. The four water conveyances in the lower reaches of the Tarim River play a positive role in the uplift of the groundwater level in the lower reaches. The groundwater level near the river channel is in a step-by-step uplift process, the horizontal influence range is about 1000 m, and the lower segment has a minor lift (6.00%). As the groundwater level rose, the response range of natural vegetation extended from 200–250 m after the first water delivery in 2000 to 800 m after the fourth delivery in 2002 (Chen et al., 2003).

Various studies have assessed the EWDP in the Tarim River Basin in different ways, and the results all showed that the EWDP has a positive effect on the restoration of the environment in the Tarim River (Chen et al., 2006; Ye et al., 2009; Liu et al., 2013). It has been confirmed that after the implementation of the EWDP, the vegetation cover and the number of species have increased significantly (Xu et al., 2004). Different vegetation types have different response distances to rivers. The perfect response distance is within 200 m, where all vegetation will respond well. Vegetation between 200 and 800 m from the riverbank showed a moderate response to the water transfer, but little response was noted for vegetation further than 800 m from the riverbank (Xu et al., 2004; Ye et al., 2005). Another study used the remote sensing and GIS techniques to assess the large-scale response of the EWDP (Bao et al., 2017); it was shown that from 2001 to 2013, the primary process of the land use change in the Tarim River Basin was the transformation from unused land to natural vegetation. The fractional vegetation coverage in 2013 was 1.5 times greater than that in 2001. It is evident that the EWDP has a positive effect in restoring vegetation in the lower reaches of the Tarim River Basin (Bao et al., 2017).

Desertification in the Tarim Basin is caused by both natural and human factors. The fragile ecological environment of the Tarim Basin is easily affected by human disturbances. The massive land reclamation resulted from the early population growth has led to an imbalance in water resource utilization (Bao et al., 2017). The upstream transition water caused the downstream cut-off, leading to a sharp drop in the groundwater level. This damaged the ecological environment in the basin, degraded the cultivated land and vegetation around the riverbank, destroyed the original balance, and accelerated the desertification process (Kasim et al., 2011, 2012). The progresses of the implementation of the EWDP in 2000 proved that these desertification processes can be reversible by utilizing proper management methods.

4   Research on sandy desertification in Xinjiang

Sandy desertification is a kind of desertification. Much research has focused on the causes of sandy desertification in Xinjiang (e.g., Tian et al., 1999; Wang et al., 2002; Zhang et al., 2003; Li et al., 2004a; Gong, 2007; Zhang et al., 2021; Lv et al., 2022). Various studies have proven that the primary reason for sandy desertification is natural factors; however, human activities are also an essential factor that cannot be ignored (Kasim et al., 2012; Zhou et al., 2015). Kasim et al. (2011, 2012) studied sandy desertification in the lower reaches of the Tarim River and concluded that human factors are the leading cause of sandy desertification. Some researchers also believed that sandy desertification was resulted from the joint action of natural factors and human activities (Xia et al., 1993; Wang et al., 2012; Zhang et al., 2015). When identifying the leading cause of sandy desertification, the time scale should be considered. Different regions and processes operating at different time scales will influence the essential factors that affect sandy desertification.

For the past few decades, sandy monitoring has mainly concentrated on two aspects: the

monitoring of aeolian sand activity and the monitoring of sandy desertification status. Many researchers have studied the issues related to the aeolian sand activity on the edges of oases (Jiang et al., 2008; Cheng et al., 2015; Yang et al., 2021). Additional research has focused on the spatial distribution characteristics of aeolian sand activity intensity in the wind-sand transition zone, the fractal characteristics of the particle size of dust shifting sand, and the differences of particle size characteristics of sand-dust material moving in different forms (Mao et al., 2013, 2016, 2018; Liu et al., 2018). The cumulative sediment transport in different height ranges was revealed through various research methods, such as regression analysis and related statistical analysis (Zhang et al., 2021), and the relationship between wind speed and sediment transport flux was established (Zhang et al., 2022). Understanding the aeolian sand activity characteristics can provide a theoretical basis for designing wind-proofing and sand-fixing projects (Mao et al., 2013, 2016; Liu et al., 2018).

Many studies have also used remote sensing and GIS techniques to identify the characteristics and changes of sandy desertification (Li et al., 2004b; Wang et al., 2017, 2021). Niu (2005) proposed two remote sensing extraction methods to assess sandy desertification degree: cover segmentation and tasseled cap transformation, and concluded that the accuracy of cover segmentation was significantly improved compared to the traditional supervised segmentation. In recent years, although different studies have used remote sensing and GIS techniques to analyze sandy desertification process in Xinjiang, the primary purpose of these studies was to identify the changes in aeolian desertified land area and its driving factors. Similar results across different regions in Xinjiang showed that human activities would affect sandy desertification (e.g., Wang et al., 2012; Amuti and Luo, 2014). Different degrees of sandy desertification may react to human activities in different ways. In contrast, most studies suggested that the primary driving factor of sandy desertification reversion is climate change, but it also depends on the degree of sandy desertification (Du and Maki, 1997; Wang et al., 2012; Amuti and Luo, 2014; Zhang et al., 2015; Zhou et al., 2015). The remote sensing and GIS techniques are helpful to analyze the drivers of sandy desertification and provide support for the reversion of sandy desertification (Li et al., 2004b; Zhang et al., 2008; Wang et al., 2017, 2021).

With the advent of remote sensing and GIS technology, the environmental management of land desertification management system was also developed. The Sandy Desertification Sensitivity Comprehensive Evaluation Index System was established through the remote sensing and GIS techniques. This system can be used to evaluate the vulnerability of arid areas, which helps to predict the process of sandy desertification, identify the high-risk regions where sandy desertification may occur, and implement windbreak and sand fixation projects (Mao et al., 2018).

Previous research related to sandy desertification in Xinjiang has proven that sandy desertification mainly occurs on the edges of oases. It is widely accepted that human activities can significantly influence sandy desertification process (Wang et al., 2012; Cheng et al., 2015; Mao et al., 2016; Liu et al., 2018). Despite the difference in study areas, multiple studies have indicated that the unreasonable utilization of water resources caused by arable land reclamation is one of the main factors that contribute to sandy desertification process (Jiang et al., 2005; Gong, 2007; Wang et al., 2009; Amuti and Luo, 2014). Rational land use, construction of ecological and environmental projects, and continuous sustainable research on land reclamation and utilization are the important approaches to solve the fundamental problem of sandy desertification. Additionally, it cannot be ignored that the monitoring of aeolian sand activity can provide a theoretical basis for designing the wind-proofing and sand-fixing projects at the present stage.

5 Research on soil salinization in Xinjiang

Soil salinization is an essential manifestation of land degradation in arid and semi-arid areas and an important factor affecting agricultural production and ecological security in these arid and semi-arid areas.

Data from the Second National Soil Survey showed that in Xinjiang, salinized cultivated land

area accounted for about 31.10% of the total cultivated land area (Li et al., 2009). This result is roughly consistent with the interpretive result of remote sensing images in 2005, which indicated that salinized cultivated land area in Xinjiang occupied 32.07% of the total cultivated land area (Li et al., 2009; Wang et al., 2009).

Regarding the natural factors, climate is the primary factor affecting soil salinization in Xinjiang. The average annual evaporation in the plain areas of northern Xinjiang is 700–1200 mm, which is 3–6 times of the annual precipitation; however, the average annual evaporation of southern Xinjiang can be as high as 1000–2000 mm, which is 7–20 times of the annual precipitation (Xu and Xu, 2005). The conditions of high temperature drying and intense evaporation suggest that the rising water flows in the soil are dominant, and the leaching and desalination process is fragile, resulting in widespread salt accumulation on the ground. Besides, rocks and soil-forming parent materials in mountainous areas generally contain salt. Through the erosion of flood or regular surface water, carbonate and gypsum with low solubility are first deposited in the upper part of the piedmont proluvial fan or pluvial alluvial plain (Hu et al., 2012). At the same time, soluble sulfate chloride easily accumulates in the middle and lower part of the abandoned cultivated land, the fluvial fan, or the pluvial alluvial plain; chloride or sulfate chloride is deposited along the fan margin below the fan margin zone. Salt in mountainous areas is brought to irrigation by surface water and groundwater, which becomes a source of soil salt supply (Zhuang et al., 2021). It should be noted that relatively high groundwater depth and high salinity are additional factors that cannot be ignored (Hu et al., 2012; Zhuang et al., 2021).

Human activities are also an important factor that accelerate the salinization process. Since the 1950s, there have been many land reclamation projects in Xinjiang, which have consumed a large amount of water. However, there is no unified scheme for water resources management, leading to an imbalance of water resources and finally the abandonment of cultivated land. Before 2000, the total reclamation area of saline-alkali wasteland in Xinjiang was 3.40×10^4 km^2, and the actual reserved area was only 1.86×10^4 km^2 (Hu et al., 2012).

New issues have evolved with irrigation development and the implementation of large-scale water-saving irrigation. During the recent land reclamation process in Xinjiang, extensive irrigation quota combined with drainage system flushing has caused the groundwater level to rise above the critical depth for a long time (Li et al., 2012). Due to the weak leaching effect under drip irrigation, it is difficult to effectively wash the salt with irrigation water (Hu et al., 2012). The salt cannot be eliminated; it can only be transferred to the soil layer. This could result in a higher salt accumulation rate of drip irrigation under film in the whole soil body than that of conventional ground irrigation (Hu et al., 2012).

Apart from the abovementioned factors, additional studies have explored different methods for monitoring soil salinity (Wang et al., 2008; Li et al., 2012). Wang et al. (2008) used geostatistics and GIS techniques to estimate the spatial variability of soil salt content around the shallow groundwater table and land use from 1983 to 2005 in Xinjiang. It was evident that the area of soil salt accumulation was more significant in irrigated land than in non-irrigated land from 1983 to 2005, with an increase of 0.43 t/(hm^2·a) in cropland and an increase of 0.68 t/(hm^2·a) in saline-alkaline land in the Fubei region. Research has shown that soil desalination rate increased significantly after building a proper drainage system, and shaft irrigation is an efficient way to control soil salinization (Wang et al., 2008). An electromagnetic induction survey was also used to identify the spatiotemporal changes in soil salinity in southern Xinjiang, and the results validated the trend effect caused by the irrigation and drainage canals and identified the soil salinity accumulation in different areas (Li et al., 2012).

Recently, more research has extended beyond monitoring with a focus on predicting and building the soil salinity model. For example, different models have been used to estimate soil salinity in different areas (e.g., Hu et al., 2012; Peng et al., 2019; Wang et al., 2019; Zhuang et al., 2021). Such research used various parameters, including satellite band reflectance, published satellite salinity indices, red-edge indices, and newly constructed two- and three-band indices from multi-stakeholder initiatives data, to set up inversion models (e.g., Li et al., 2012; Wang et al., 2019).

Various algorithms have also been studied in the model-building process, ultimately confirming that the forest random-partial least squares regression model has the best accuracy (e.g., Wang et al., 2018; Peng et al., 2019). Applying the forest random-partial least squares regression model showed that soil salinity in the dry season was higher than that in the wet season, mainly in the Ebinur Lake area (Wang et al., 2018). Another study also set up the Cubist and partial least squares regression models on electrical conductivity to estimate soil salinity in southern Xinjiang (Peng et al., 2019). Wang et al. (2019) compared the Cubist and partial least squares regression models for monitoring soil salinity in southern Xinjiang and suggested that the Cubist model has a more detailed spatial distribution of electrical conductivity than the partial least squares regression model.

Based on the results above, more researchers have developed methods to mitigate salinization (e.g., Liu et al., 2012; Zhang et al., 2020). The first method centers around implementing water conservancy projects, including establishing a complete irrigation and drainage system (Liu et al., 2012). Therefore, under the condition of long-term drip irrigation and film, the maintenance and construction of the existing drainage system should be strengthened, and attention should be paid to the comprehensive application of various salt suppression technical measures (Zhang et al., 2020).

Second, biological improvement measures have been widely used to mitigate salinization, mainly including afforestation, planting pastures, and cultivating salt-tolerant plants. Salt-tolerant plants can lower groundwater level, increase surface coverage, reduce ground evaporation, and prevent soil surface salinity through biological drainage (Yang et al., 2019). Research has shown that biological irrigation through planting salt-tolerant trees and shrubs with high humidity efficiency and evapotranspiration rate is also an effective measure for improving saline-alkali land (Zheng et al., 2020).

Third, chemical measures are also effective ways to control soil salinization. Chemical improvement measures mainly apply gypsum, phosphoric acid, slag, and/or other beneficial materials in salinized soil to reduce soil salt content. The sodium in the soil can then be replaced through ion substitution before being washed away by irrigation, thus improving the saline-alkali soil. Chemical improvement measures are generally reserved to improve the most severely saline-alkali soils. However, there is still a lack of in-depth research on the application mode of chemical amendments and the effects of applications in different saline-alkali soils (Hua et al., 2019).

6 Desertification control management in Xinjiang

6.1 Comprehensive control of sand and dust source areas in Xinjiang

The sand and dust source areas in Xinjiang are mainly distributed in the Taklimakan Desert and its transition zone, the Turpan-Hami Basin and its southern area, the Kumtag Desert and its northern area, the Gurbantunggut Desert, and the eastern Karamay City. In addition, the middle and lower reaches of rivers and their tail areas, as well as dry lake basins, such as the mainstream areas of the Tarim River, Lop Nur, Taitma Lake, and the surrounding areas of the Ebinur Lake, are also the main areas for sand and dust release in Xinjiang.

Management of sand and dust source areas is a systematic project with multiple measures. First, it is necessary to strictly limit the disturbance of the land surface caused by human activities. Second, it is essential to strengthen the regulation and management of water resources in the river basins. Third, enhancing the restoration and protection of regional ecosystems is necessary. Fourth, it is important to accelerate the rehabilitation and reconstruction of damaged ecosystems and the restoration of degraded land.

6.1.1 Soil wind erosion control in the mainstream of the Tarim River

The mainstream of the Tarim River and its tail area are mainly affected by natural factors and human activities, such as the change of the mainstream of the Tarim River and the over-utilization of water resources, which has caused the degradation of *Populus euphratica* forests in both sides of the

upper and middle reaches of the mainstream of the Tarim River. Moreover, it also leads to the expansion of bare land in the lower reaches of the Tarim River and the drying up of the Taitma Lake, aggravating soil wind erosion and sand and dust release. Soil wind erosion control in the mainstream of the Tarim River and its tailing area should be coordinated with the water resources management and ecological improvement projects in the Tarim River Basin, from joint prevention and control across departments and regions. The main measures include: (1) expanding the overflow range of the middle reaches of the mainstream of the Tarim River and the ecological water delivery area in the lower reaches of the Tarim River; (2) establishing contiguous prohibited protected areas of desertified land; (3) strengthening the restoration and protection of degraded vegetation, especially *P. euphratica*; (4) implementing surface fixation projects in areas with severe soil wind erosion; and (5) establishing an integrated protection system for rivers, lakes, and roads in the lower reaches of the Tarim River.

6.1.2   Salt and dust source control in the dry lake basin around the Ebinur Lake

The Ebinur Lake is located in the Bortala Mongolian Autonomous Prefecture of Xinjiang, with Alashankou City in the west and Gurbantunggut Desert in the east. Due to the decrease in the amount of water entering the lake from the Bortala River, Jinghe River, and Kuytun River, the area of the Ebinur Lake has shrunk by a large extent, the vegetation in the lakeside area has been degraded, and the land has dried up, resulting in the activation of sand dunes and the intensification of soil wind erosion.

In recent years, the lake area has been restored with the construction of the Ebinur Lake Wetland National Nature Reserve, and the lakeside ecology has been improved significantly. However, due to the downwind of Alashankou, sand and dust weather is frequent here. The control of salt and dust sources in the dry lake basin around the Ebinur Lake should be combined with its neighbor area, such as the Ganjia Lake *Haloxylon* Forest National Nature Reserve. The main measures for the salt and dust source control in the dry lake basin around the Ebinur Lake include: first, increasing the overflow intensity of the Ebinur Lake; second, strengthening the restoration and protection of lakeside vegetation outside the nature reserves; third, strictly controlling the surface disturbance of the dry lake basin; and fourth, improving the construction of the shelter forest system around the dry lake basin.

6.2   Desert edge locking project in Xinjiang

It is a common phenomenon that quicksand expands outwards and activates fixed sand dunes in Xinjiang. In history, the intrusion of the Taklimakan Desert has led to the three relocations of Qira County in Hotan Prefecture of southern Xinjiang. There is also a sand dune activation zone on the southern edge of the Gurbantunggut Desert, and the quicksand continues to move towards the surrounding oases.

The critical points of the desert edge locking project are as follows: (1) fixing the vegetation on the edges of the semi-fixed deserts, so that the activated sand surface can be repaired and the vegetation can be restored; and (2) implementing the ecological restoration and reconstruction on the edges of the mobile desert to prevent the shifting sand from moving to the oases and threatening the cultivated land.

6.2.1   Vegetation enclosure and conservation on the southern edge of the Gurbantunggut Desert

The Gurbantunggut Desert is the largest fixed and semi-fixed desert in China. Due to human disturbances, such as overgrazing, logging, infrastructure construction, etc., the issue of sand dune activation is serious, especially on the southern edge of the desert. The main measures of vegetation enclosure and conservation on the south edge of the Gurbantunggut Desert include: first, establishing contiguous enclosed protection areas of desertified land; second, implementing vegetation enclosure and conservation on the southern edge of the desert; and third, strengthening the construction of ecological barriers around the desert for the ecological restoration of cultivated land.

6.2.2   Ecological restoration and reconstruction on the southern edge of the Taklimakan Desert

The Taklimakan Desert is the second largest mobile desert in the world, especially on the southern

edge of the Taklimakan Desert, where sand dune activity is high. It is affected by the northwest airflow over the Pamirs and the eastern irrigation airflow in the eastern part of the Tarim Basin. In addition, vegetation on the edges of the desert is degraded, and the quicksand is approaching the oases. The edge even partially crosses the shelterbelts and enters the cultivated land. Thus, the ecological restoration and reconstruction project should be implemented on the southern edge of the Taklimakan Desert. The main measures include: (1) limiting human disturbances to the southern edge of the desert; (2) strengthening vegetation restoration on the southern edge of the desert; (3) improving the ecological construction and vegetation protection in the desert-oasis transition zone; and (4) establishing enclosed protection areas of desertified land on the edges of oases and in the both sides of the lower reaches of rivers.

7 Conclusions

Desertification in Xinjiang can be attributed to both natural factors and human activities. The main desertification issues in Xinjiang are the activation and expansion of deserts and soil wind erosion. Several factors may lead to the activation and expansion of deserts, which include cut-off and shortened flow of the river, shrinkage of desert-oasis transition zone resulted from human activities, and sand dune activation caused by overgrazing. For instance, the cut-off of the Tarim River and Manas River has caused significant damage to the regional ecological environment, leading to rapid land degradation in the downstream areas. Furthermore, it also caused the worsening of soil salinization around the river channels and activated the surrounding sand dunes.

Soil wind erosion in Xinjiang is manifested as desertification of grassland and existing cultivated land, activation of fixed and semi-fixed sand dunes, and degradation of desert riparian forests. All of these kinds of desertification occurred due to the destruction of the balance of the regional system. For example, due to the continuous expansion of artificial oases, human activities have led to the destruction of vegetation in the past 20 years, and the activation area of fixed and semi-fixed sand dunes in the Gurbantunggut Desert in northern Xinjiang has continued to increase, especially on the southern edge of the desert. One of the main factors is the change in the distribution of water resources. The shortage and unreasonable utilization of water resources, especially the contradiction between production water and ecological water use, have not been resolved for a long time, resulting in the fragment of the ecological environment, the degradation of natural vegetation, severe soil drought and salinization, wind erosion, and desertification.

Through the review of desertification research in Xinjiang, there are two primary forms of desertification: soil salinization inside oases and sandy desertification on the edges of oases. These are the essential issues that should be of concern in Xinjiang. In recent years, the focuses of desertification control in Xinjiang have been to formulate different control strategies according to the different manifestations of desertification. For desertification control, several key points are suggested: first, strengthening the management of the desert ecological environment to prevent the activation of sand dunes and the expansion of deserts; second, improving the rational allocation of water resources and restoring the stability of the ecosystem; third, optimizing the overall sand control strategy by combining with the experience of successful desert control projects.

It should be noted, however, that desertification is an evolving process in continuous development. Reversion and degradation occur at the same time, even in the same region. Therefore, it is essential to study the overall mechanism of desertification on a larger scale, because taking the mechanisms of desertification research on a larger scale can better help to employ desertification control measures.

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